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HIGH-ALTITUDE COOLING

IV - INTERCOOLERS

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SUMMARY

The variation of intercooling requirements with altitude is discussed and the corresponding effects on intercooler design are shown. A discussion is also given of the relations among the various design parameters and of the ranges of choice in design. The important effects of the various factors on intercooler proportions are illustrated with charts for the Harrison copper cross-flow intercooler.

INTRODUCTION

Analysis of intercooler design for high-altitude operation involves not only consideration of the altitude effects discussed in the other papers of this series (references 1 to 5) but also consideration of the fact that the heat-dissipation requirement itself, unlike that of the other cooling elements, increases with altitude. The purpose of this paper is to discuss this variation of the intercooling requirements with altitude and to show the corresponding effects on intercooler design. Inasmuch as considerable latitude exists in intercooler design, the discussion of the altitude effect has been supplemented with a discussion of the interrelationships of the design parameters. Some remarks concerning intercooler types and construction have also been included.

The discussion has been illustrated with a number of charts for the Harrison copper cross-flow intercoolers, calculated according to the theory and methods of reference 6. Inasmuch as the charts are mainly illustrative, no effort was made in their calculation to take into account the temperature and compressibility effects on the pressure drop. The resulting error will usually be relatively small for altitudes up to 40,000 feet because of the relatively low airspeeds through intercoolers.

SYMBOLS

L_c length of cooling-air passage, inches

L_e length of engine charge-air passage, inches

L_n no-flow length of intercooler, inches

M_c weight rate of flow of cooling air

M_e weight rate of flow of engine charge air

p_1 supercharger intake total pressure, pounds per square foot

p_2 supercharger discharge total pressure, pounds per square foot

Δp_c cooling-air pressure drop through intercooler

Δp_e engine charge-air pressure drop through intercooler

T_o temperature of free stream, $^{\circ}$F absolute

T_1 temperature of cooling air entering intercooler and also of engine air entering supercharger, $^{\circ}$F absolute

T_2 temperature of engine charge air at supercharger outlet, $^{\circ}$F absolute

T_3 temperature required of engine charge air at carburetor, $^{\circ}$F absolute

V_o velocity in free stream, feet per second

η_{ad} adiabatic efficiency of supercharger

ξ ratio of temperature drop of engine charge air to temperature difference between engine charge air and cooling air at their entrance to intercooler $\left(\frac{T_2 - T_3}{T_2 - T_1}\right)$

COOLING REQUIREMENTS AND INTERCOOLER EFFECTIVENESS

The performance required of an intercooler is defined by the effectiveness ξ, which is the ratio of the temperature drop of the charge air to the temperature difference between the charge air and the cooling air at their entrance to the cooler:

$$\xi = \frac{T_2 - T_3}{T_2 - T_1} \tag{1}$$

The cooling-air temperature T_1 as explained in reference 3 is the stagnation temperature given by

$$T_1 = T_o + 0.832 \left(\frac{V_o}{100}\right)^2 \tag{2}$$

in which the subscript o denotes free-stream conditions.

The temperature of the supercharger discharge T_2 is

$$T_2 = T_1 \left[\frac{\left(\frac{p_2}{p_1}\right)^{0.286} - 1}{\eta_{ad}} + 1\right] \tag{3}$$

The outlet-air temperatures as computed from equation (3) for a typical supercharger installation are shown plotted against altitude in figure 1. In obtaining the adiabatic temperature rise used in constructing figure 1, the high-speed performance of a typical pursuit airplane as given by table I of reference 3 was assumed. Curves showing the temperatures that would occur with 100-percent adiabatic efficiency have been added for comparison. These curves show that, for flight at 500 miles per hour in Army air at 40,000 feet, the discharge from a supercharger of 100-percent adiabatic efficiency would be 112° F higher than a specified carburetor temperature of 100° F and that the discharge temperature from a supercharger of 65-percent adiabatic efficiency is even higher by another 130° F.

The effectiveness required of an intercooler is derived from equations (1), (2), and (3), as

$$\xi = 1 - \eta_{ad}\left[\frac{\frac{T_3}{T_1} - 1}{\left(\frac{p_2}{p_1}\right)^{0.286} - 1}\right] \tag{4}$$

and is shown in figure 2 for a wide range of altitudes and true airspeeds for flight in Army air with a supercharger efficiency of 0.65 and a carburetor-air temperature of 100° F.

Values of the required intercooler effectiveness, obtained from figure 2, are shown in figure 3 plotted against altitude for both high-speed and climbing flight of the typical pursuit airplane of reference 3. The extreme flatness of these effectiveness curves for both high-speed and climbing flight is characteristic of turbo-supercharging with its continuously variable supercharger speeds. Gear-driven superchargers employing the throttle method of control require intercoolers of higher effectiveness than those adequate for variable-speed superchargers, except at the critical altitude.

Values of intercooler effectiveness may be readily corrected for changes in supercharger efficiency by a relation derived from equation (4). For any given set of conditions of temperature and pressure the relation is

$$\frac{1 - \xi}{\eta_{ad}} = \frac{1 - \xi'}{\eta_{ad}'} \tag{5}$$

where ξ' is the new value of intercooler effectiveness corresponding to a new value of adiabatic efficiency η_{ad}'. This relation may be transposed as follows for greater convenience:

$$\xi' = 1 - (1 - \xi)\frac{\eta_{ad}'}{\eta_{ad}} \tag{6}$$

INTERCOOLER TYPES AND CONSTRUCTION

The type of intercooler in general use is the cross-flow type, in which the cooling air and the charge air flow in parallel planes at right angles to each other. The fundamentally best type of heat exchanger, however, is the counterflow type, in which the two flows of air are also in parallel planes but in opposite directions. A comparison of the two types of heat exchanger on the basis of required heat-transfer surface is shown in figure 4 (data from reference 7), where the advantage of the counterflow type is seen to be considerable for the higher values of effectiveness. This theoretical advantage, considered with the greater adaptability and greater freedom in the choice of proportions of the counterflow intercooler, may in certain cases outweigh the advantage of simplicity of construction of the cross-flow type. The possibilities of the counterflow type accordingly should not be overlooked.

In some cross-flow intercoolers the charge air flows through a battery of tubes and the cooling air flows over the outside of the tubes. The tubes are circular, elliptical, or flattened to such a degree as to constitute effectively parallel plates. In the Harrison type of intercooler, which has been selected for this analysis, the charge air and the cooling air are separated by parallel plates that are spaced and reinforced by metallic ribbons acting as fins to increase the heat-transfer surface. The cooling-air and the charge-air passages are identical in cross section and differ only in length. Dissimilarity between engine charge-air and cooling-air passages such as is found in other types of intercooler will modify somewhat the basic dimensions of the unit; but similar trends in the variation of dimensions with altitude, effectiveness, or pressure drop will occur.

THE EFFECT OF ALTITUDE ON INTERCOOLER DIMENSIONS

The effect of design altitude on the intercooler dimensions is shown by figures 5 and 6 for the variation in effectiveness with altitude shown in figure 3. Figure 5 is based on cooling-air and charge-air pressure drops of 40 pounds per square foot, which is believed to be the minimum practicable value, and figure 6 is based on pressure drops of 70 pounds per square foot, which is about the maximum usually obtainable at the critical altitude. Greater flow lengths at low altitudes are a consequence of the high effectiveness required. It is normally considered impractical to design intercoolers for this condition and some reduction in engine power at low altitudes is unavoidable on hot days.

Above 20,000 feet the flow lengths required are almost independent of the design altitude, the principal effect being an increase in no-flow length. For the case demonstrated, the no-flow dimension increases approximately with the cube root of the design altitude.

RELATIONSHIPS AND RANGES OF DESIGN

FOR A GIVEN ALTITUDE

There are eight interrelated major variables involved in the design of intercoolers: engine-air flow, effectiveness, engine-air pressure drop, cooling-air pressure drop, cooling-air flow, and the three linear dimensions of the intercooler. For any given type of core construction only five of these variables can be independent. The engine-air flow and the required effectiveness are basic parameters. The engine- and cooling-air pressure drops are secondary parameters in which some variation is permitted. Of the four remaining variables – the cooling-air flow and the three intercooler dimensions – one may be fixed by practical design considerations; the other three are then determined for the given set of values of the first four parameters.

The relationship between the variables is illustrated for high-speed flight of the typical pursuit airplane in Army air at 40,000 feet by the curves of figures 7 to 10. The effect on the dimensions of the intercooler of varying the amount of the cooling air is shown by the solid lines of figure 7 for a pressure drop of 40 pounds per square foot on each side of the intercooler. This figure shows the great increase of the no-flow dimension and the comparatively small decrease in the length of the engine-air and the cooling-air passages with increasing cooling-air flow.

The broken lines of figure 7 show the intercooler dimensions for the case of a 70-pound-per-square-foot pressure drop for both engine air and cooling air. Where these higher pressure drops are permissible, the reduction in necessary no-flow length of the intercooler is marked, but the advantage of smaller frontal area and lower weight so obtained must be weighed against the disadvantage of greater cooling drag.

In order to demonstrate more clearly than is shown in figures 5 to 7 the relation of intercooler size to design pressure drop, figures 8 and 9 are presented. These figures show the individual effects of engine-air and cooling-air pressure drop. An increase in either engine-air or cooling-air design pressure drop appreciably reduces the required no-flow length with little change in the other two dimensions.

The effect on the intercooler dimensions of a change in required effectiveness is shown in figure 10 for pressure drops of

40 pounds per square foot for both engine and cooling air. Such a change in required effectiveness might be brought about, for example, by a change in the supercharger efficiency or by a change in the carburetor-air temperature requirements. Thus, an increase in η_{ad} from the assumed value of 0.65 to a value of 0.77 would reduce the required intercooler effectiveness of 0.705 used for figure 7 to 0.65, which for a mass-flow ratio of 2 results in decreasing the intercooler volume from 5.75 to 4.10 cubic feet. A decrease of 10° F in the desired carburetor-air temperature would require an increase in intercooler effectiveness to 0.735, which for the same mass-flow ratio of 2 would increase the volume to 6.8 cubic feet. Although some reduction in no-flow length occurs with increasing effectiveness, the volume of the intercooler increases because of the increase in both flow lengths. From considerations of airplane performance, intercoolers of effectiveness greater than 75 percent are undesirable, as shown in reference 8.

An extended treatment of the subject of design variables is given in reference 9.

CONCLUDING REMARKS

The limits on available cooling-air pressure drop are set by airplane performance, and one or more of the maximum intercooler dimensions are governed by the space available in the airplane. The remaining intercooler dimensions and the rate of flow of cooling air are the principal variables to be adjusted by the designer in meeting the intercooling requirements. The final choice will be a compromise between intercoolers that have small volume, great length in the no-flow dimension, and use large quantities of cooling air, and intercoolers that have more convenient proportions, use less air, but are excessively heavy. For the type of core under discussion, the best compromise will frequently be found at a ratio of cooling-air mass flow to engine-air mass flow of about 2.

High-altitude design produces a marked effect on the no-flow dimension and the volume of air handled. For the type of intercooler examined, the no-flow dimension at a constant pressure drop and constant mass flow of cooling air varies approximately with the cube root of the design altitude. In general, an intercooler designed for high altitudes will be larger and heavier than one selected for use only at lower altitudes. At any given altitude, however, the cooling-power requirement of the unit designed for high altitude will be less than that of the unit selected for use at only low altitudes.

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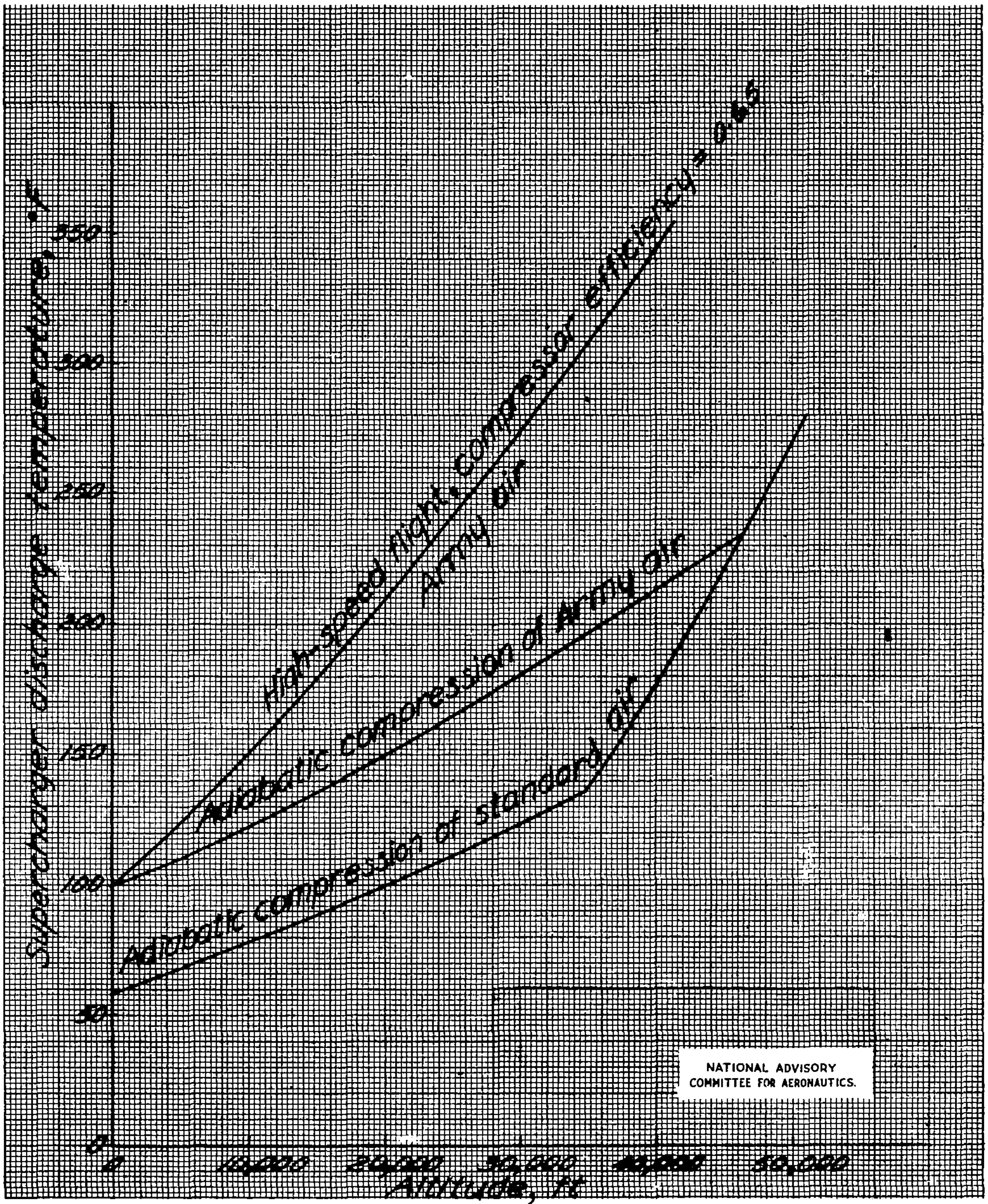

Figure 1.— Comparative supercharger discharge temperature for discharge pressure of 2116 pounds per square foot.

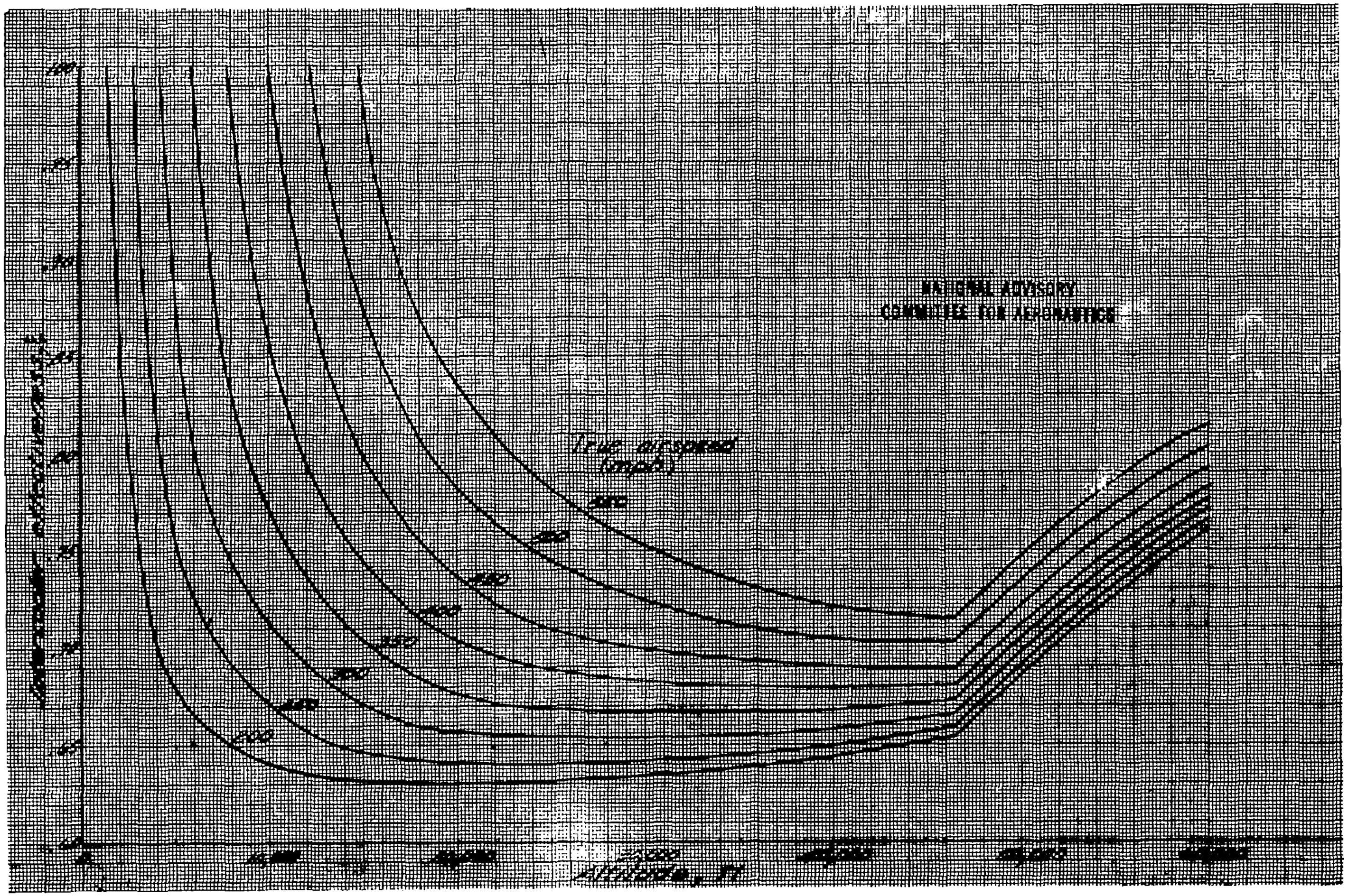

Figure 2.– Intercooler effectiveness for Army air as a function of speed and altitude. Supercharger discharge pressure, 2116 pounds per square foot; carburetor temperature, 100°F, 90 percent recovery of free-stream dynamic pressure with full adiabatic temperature rise.

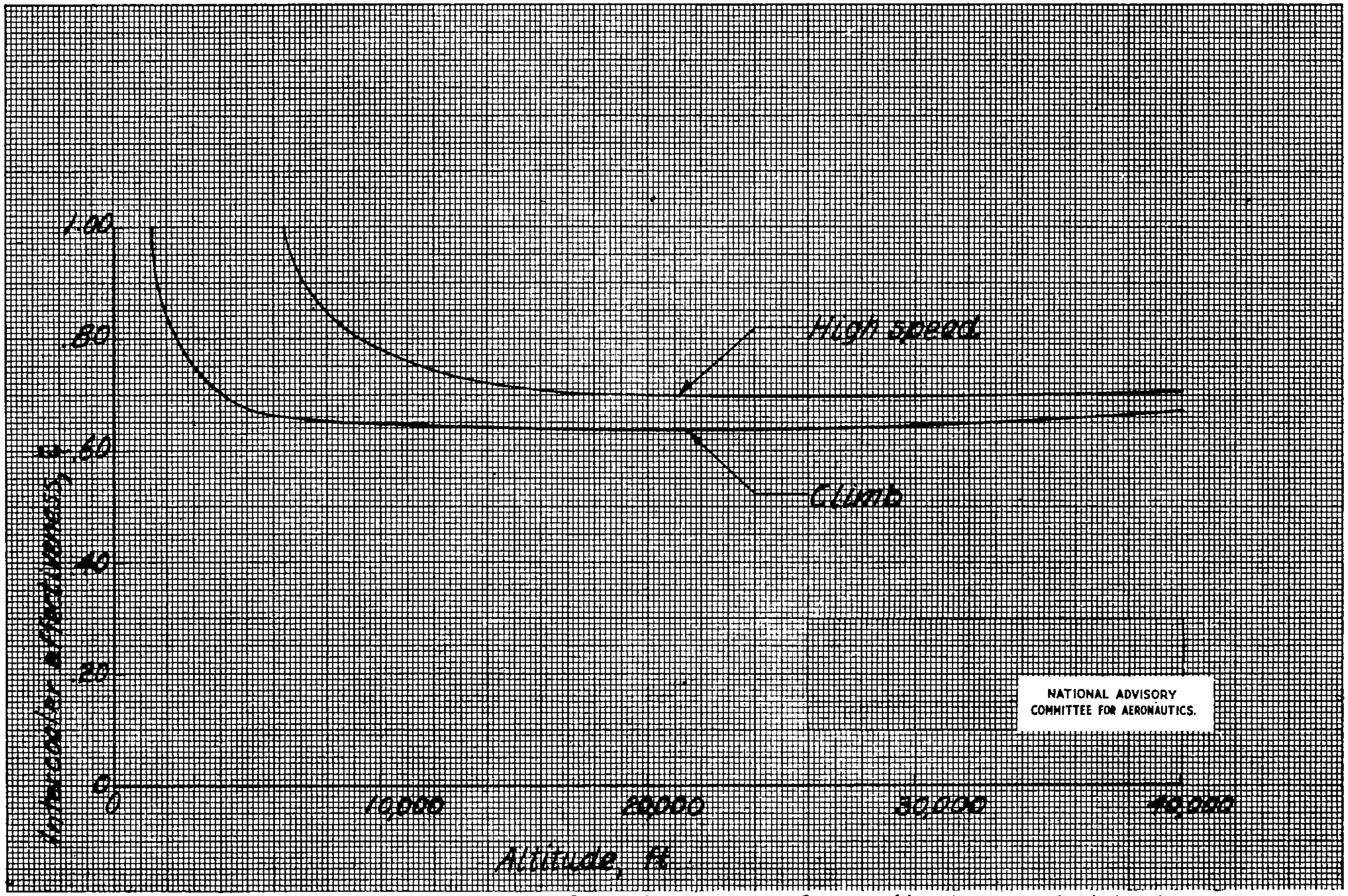

Figure 3.– Intercooler effectiveness for climb and high speed of typical pursuit airplane. (Derived from fig. 2.)

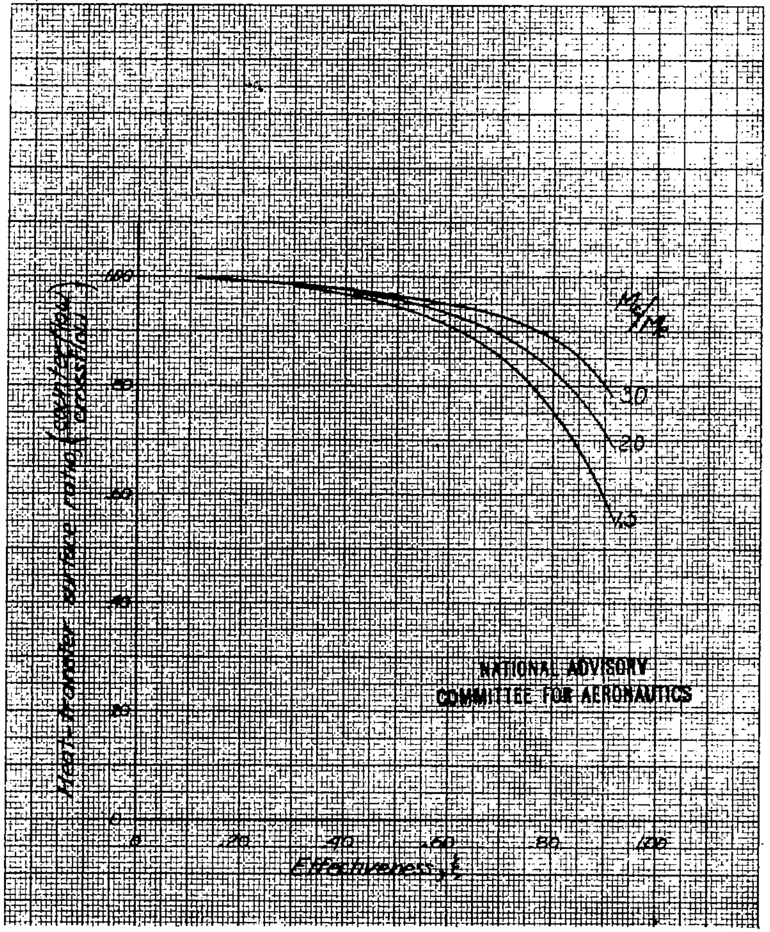

Figure 4.—Comparison of crossflow and counterflow intercooling.

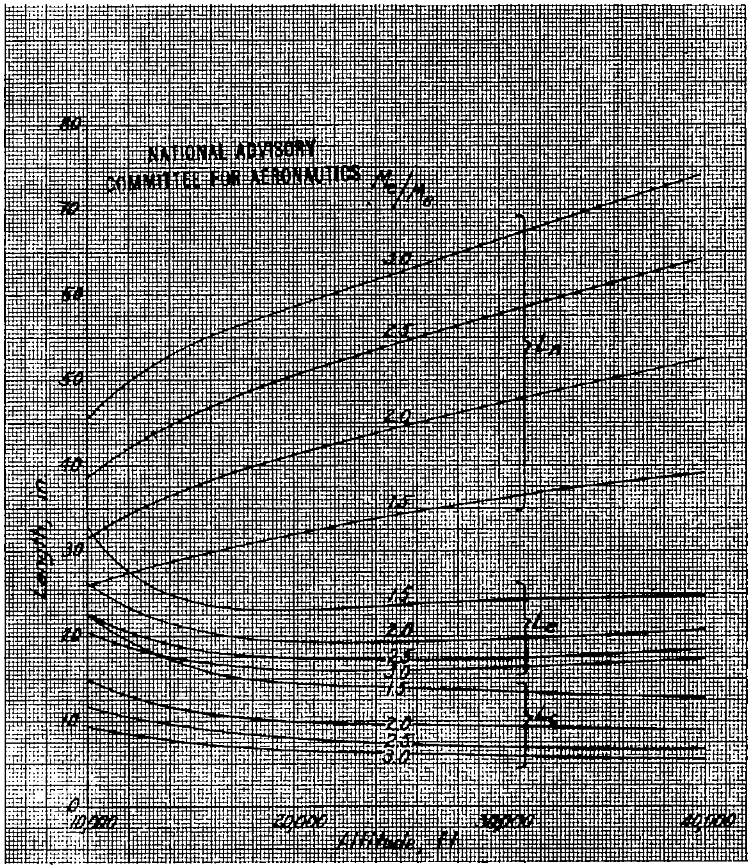

Figure 5.—Variation of intercooler dimensions with altitude for pressure drops of 40 pounds per square foot for both engine charge air and cooling air. Effectiveness for the high-speed condition from figure 3.

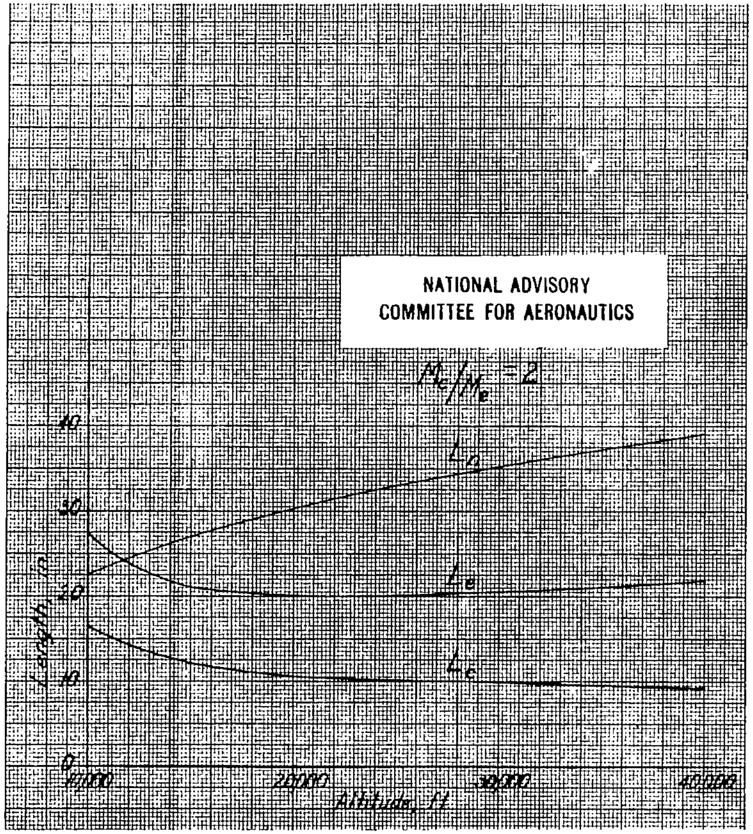

Figure 6.–Variation of intercooler dimensions with design altitude for pressure drops of 70 pounds per square foot for both engine charge air and cooling air. Effectiveness for the high-speed condition from figure 3.

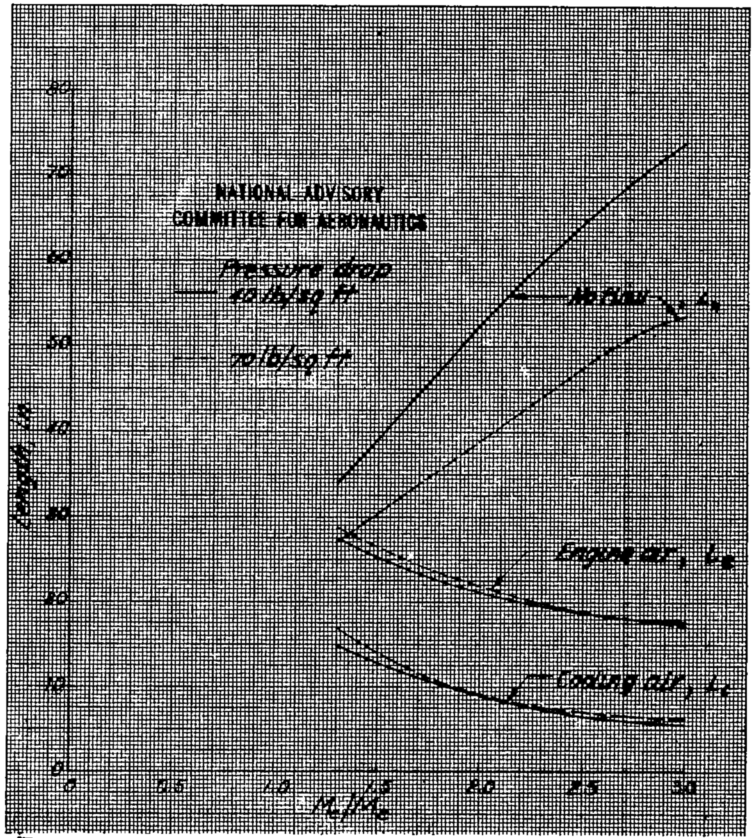

Figure 7.–Effect of cooling-air flow on intercooler dimensions for pressure drops of 40 pounds per square foot and 70 pounds per square foot. Altitude, 40,000 feet; speed, 500 miles per hour; $\xi = 0.705$.

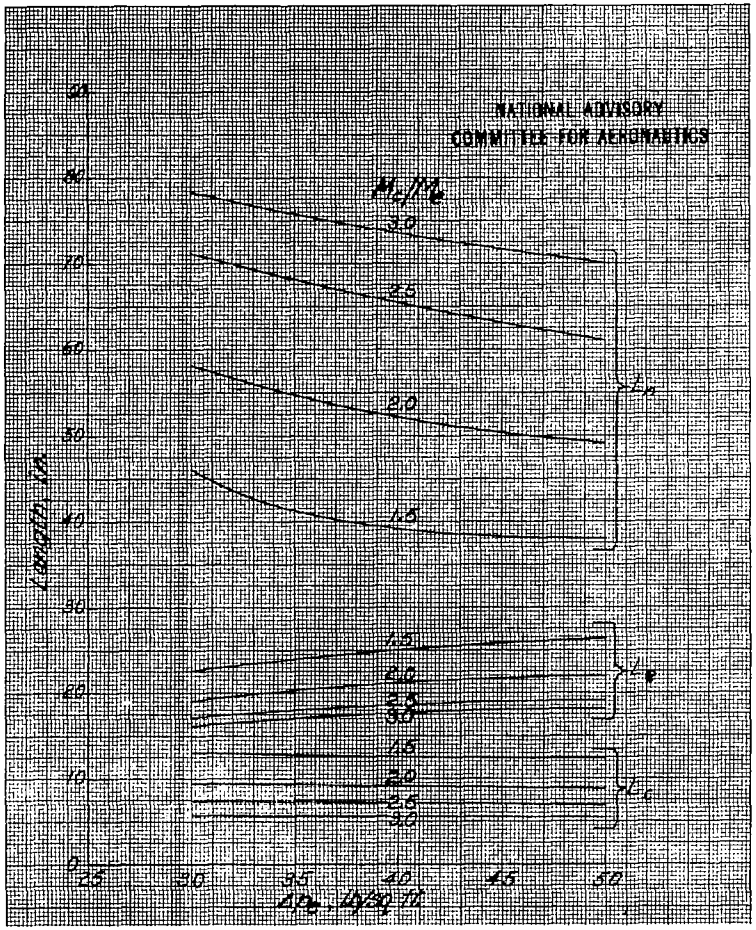

Figure 8.—Effect of engine-air pressure drop on intercooler dimensions. Altitude, 40,000 feet; Δp_c, 40 pounds per square foot; $\xi = 0.705$.

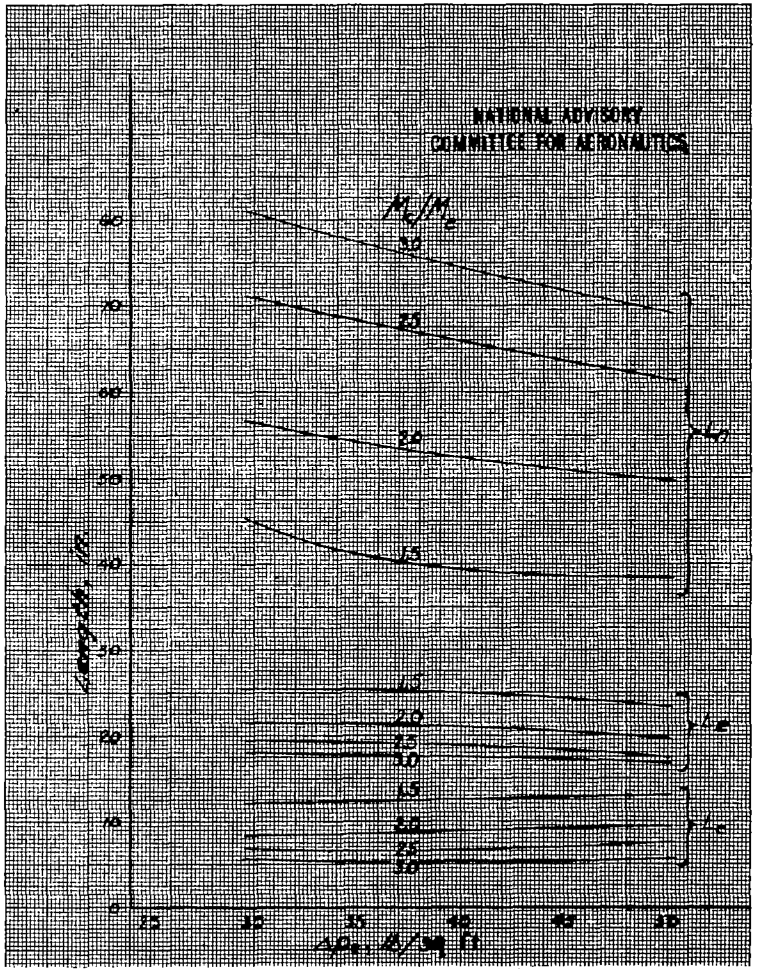

Figure 9.—Effect of cooling-air pressure drop on intercooler dimensions. Altitude, 40,000 feet; Δp_e, 40 pounds per square foot; $\xi = 0.705$.

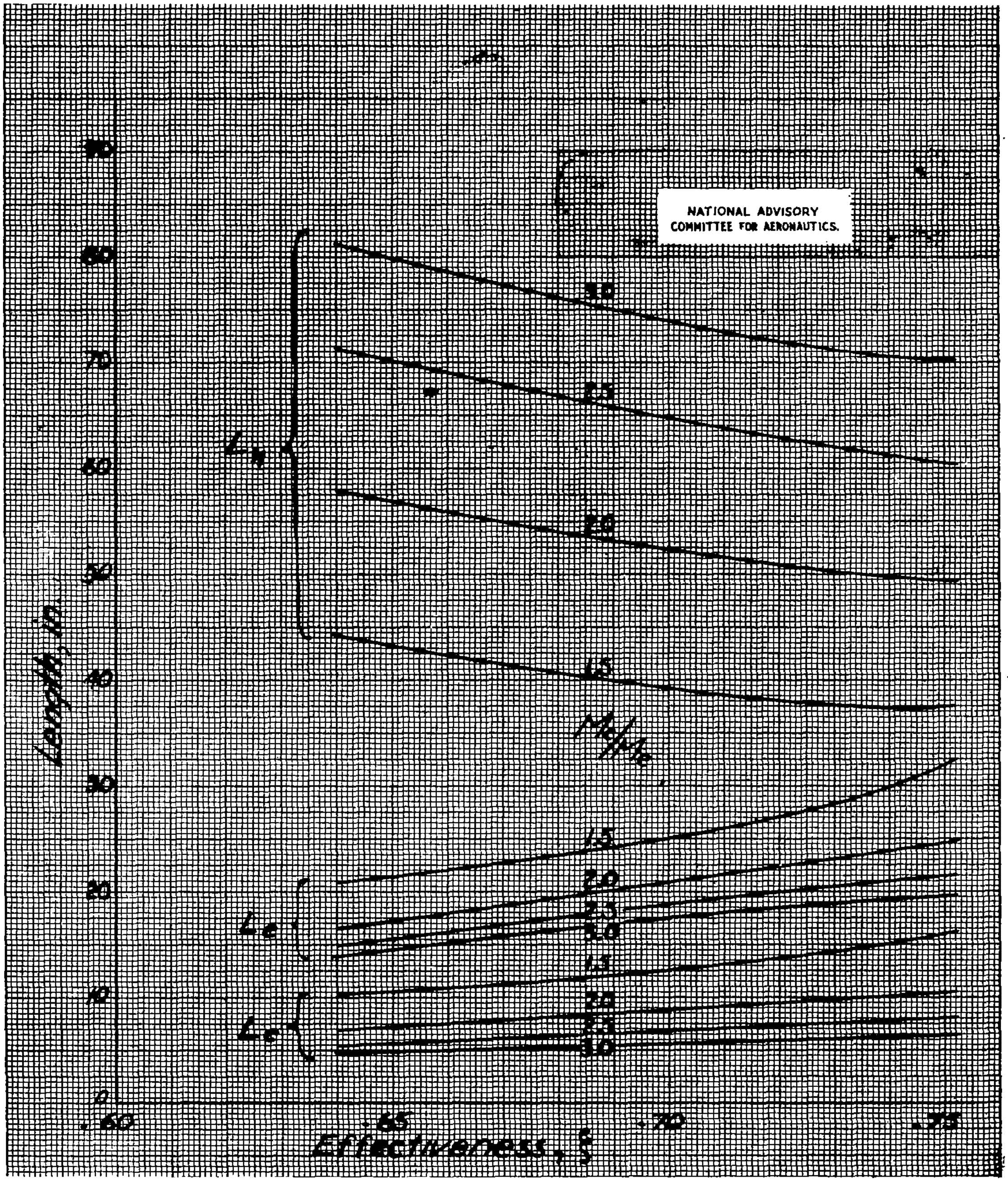

Figure 10.—Influence of required effectiveness on intercooler dimensions. Altitude, 40,000 feet; $\Delta p_c = \Delta p_e = 40$ pounds per square foot.